Solar Array Disturbances to Spacecraft Pointing during the Lunar Reconnaissance Orbiter (LRO) Mission

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The Lunar Reconnaissance Orbiter (LRO), the first spacecraft to support NASA's return to the Moon, launched on June 18, 2009 from the Cape Canaveral Air Force Station aboard an Atlas V launch vehicle. It was initially inserted into a direct trans-lunar trajectory to the Moon. After a five day transit to the Moon, LRO was inserted into the Lunar orbit and successfully lowered to a low altitude elliptical polar orbit for spacecraft commissioning. Successful commissioning was completed in October 2009 when LRO was placed in its near circular mission orbit with an approximate altitude of 50km. LRO will spend at least one year orbiting the Moon, collecting lunar environment science and mapping data, utilizing a suite of seven instruments to enable future human exploration. The objective is to provide key science data necessary to facilitate human return to the Moon as well as identification of opportunities for future science missions. LRO's instrument suite will provide the high resolution imaging data with sub-meter accuracy, highly accurate lunar cartographic maps, mineralogy mapping, amongst other science data of interest.

LRO employs a 3-axis stabilized attitude control system (ACS) whose primary control mode, the "Observing Mode", provides Lunar nadir, off-nadir, and inertial fine pointing for the science data collection and instrument calibration. This controller combines the capability of fine pointing with on-demand large angle full-sky attitude reorientation. It provides simplicity of spacecraft operation as well as additional flexibility for science data collection. A conventional suite of ACS components is employed in the Observing Mode to meet the pointing and control objectives. Actuation is provided by a set of four reaction wheels developed in-house at NASA Goddard Space Flight Center (GSFC). Attitude feedback is provided by a six state Kalman filter which utilizes two SELEX Galileo Star Trackers for attitude updates, and a single Honeywell Miniature Inertial Measurement Unit (MIMU) to provide body rates for attitude propagation. Rate is computed by differentiating accumulated angle provided by the MIMU.

The Observing Mode controller is required to maintain fine pointing while a large fully-articulated solar array (SA) maintains its panel normal to the solar incidence. This paper describes the disturbances to the attitude control resulting from the SA articulation. Observing Mode performance in the presence of this disturbance was assessed while the spacecraft was in an initial elliptical low altitude orbit during the commissioning phase, which started about two weeks after launch and lasted for 90 days. LRO demonstrated excellent pointing performance during Observing Mode nadir and inertial attitude target operations during this phase. Transient LRO attitude errors observed during commissioning resulted primarily from three sources, Diviner instrument calibrations, RW zero crossings, and SA articulation. Even during times of considerable disturbance from SA articulation, the attitude errors were maintained below the statistical attitude error requirement level of 15 arc-sec (3 sigma).

System performance during typical nadir targeting exhibited somewhat increased pointing errors during the times when the SA was tracking the Sun. The largest rate transients observed were

due to two step jumps in the commanded elevation angle. Generally, the SA elevation gimbal is stopped during nadir target operations. Integrator wind-up due to small one-step tracking error offsets resulted in very low frequency limit cycling, with amplitude of two cardinal steps (~0.015 deg). Each two-step disturbance resulted in rate transients of about 30-40 arc-sec/sec about the roll axis and 20-30 arc-sec/sec about the yaw axis. These rates were somewhat large, but still within the LRO stability requirements. The primary disturbance from the SA azimuth gimbal drive was due to the harmonic drive gear transmission error disturbance. Since the azimuth gimbal is continuously rotating at orbital rate to track the Sun this gear transmission error occurs primarily about the body pitch axis. This error is caused by a sustained SA oscillation driven at harmonics of the SA gimbal drive speed due to complex interaction of the harmonic drive flexible spline with the circular spline. The dominant disturbance associated with this mechanism occurs at a 2x harmonic of the SA azimuth gimbal drive rate, with a period of approximately 15 to 20 sec. This disturbance caused a maximum attitude error of ~11 arc-sec over a typical orbit during the commissioning phase. The attitude error builds up shortly after the starting the SA rewind when the SA azimuth gimbal reverses direction. While this error was predicted prior to flight it was somewhat surprising that the magnitude of the error seemed to be dependent on the direction of gimbal rotation and perhaps the loading of the gears during the reversal. This gear transmission disturbance trended somewhat lower as the solar beta angle decreased due to the reduced inertia loading about the +Y gimbal axis. Since this error was primarily at a low frequency of about 0.05 Hz a solution involving modification of the controller filters and gains was proposed to attenuate this disturbance. In addition to increasing the closed loop bandwidth, this solution also involved implementing a disturbance rejection filter tuned to the 2x harmonic. This solution appeared to be feasible but was not implemented since the Observing mode performance was within the design requirements.

Since the LRO is nadir pointing in a polar orbit the SA +Y gimbal reverses direction twice an orbit over the lunar poles. The attitude disturbance resulting from this SA “rewind” is minimized by using acceleration profiling in the gimbal control electronics. As the SA approaches the rewind condition the gimbal rate is slowly reduced to zero over a period of about two minutes. After stopping for a few minutes, the SA reversed, slowly increased its rate again over a two minute period. Rate spikes, of ~20 arc-sec magnitude, occurred at the end of deceleration and beginning of acceleration from the stopped condition due to the drive having a non-zero minimum rate. The attitude transients due to the SA rewinds were typically less than 10 arc-sec.